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Temporal changes in mortality impacts of heat wave and cold spell in Korea and Japan

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ABSTRACT

Investigating how well people adapt to heat waves and cold spells has been an important issue under climate change. Also, most of previous studies focused only on the mortality risks for heat waves or cold spells for certain time period not considering its temporal changes and increasing frequencies. This study investigated the change in risks of mortality from heat waves and cold spells over time, and estimated the temporal changes in mortality burden attributed to heat waves and cold spells in Korea and Japan. We collected time-series data covering mortality and weather variables from 53 communities in the two countries from 1992 to 2015. Two-stage time-series regression with a time-varying distributed lag model and meta-analysis was used to assess the impacts of heat waves and cold spells by period (1990s, 2000s, and 2010s). In total population, the risks of heat waves have decreased over time; however their mortality burden increased in the 2010s compared to the 2000s with increasing frequency. On the other hand, the risk and health burden of cold spells have increased over the decades. Our findings showed that the future mortality burden of heat waves and cold spells might not decrease, when considering their changes in risks and frequencies.

1. Introduction

Heat waves and cold spells are prominent threats to human health. Many studies have reported that the positive association between extreme weather and mortality (Analitis et al., 2014; Anderson and Bell, 2009; Barnett et al., 2012; Huynen et al., 2001; Le Tertre et al., 2006; Semenza et al., 1996; Xie et al., 2013). A recent study found that 48–74% of the world's population will suffer from heat waves in 2100 (Mora et al., 2017), and other studies discovered the shift of the polar vortex over the last several decades, which could lead to increasing cold spells in mid-latitude regions (Cohen et al., 2014; Wallace et al., 2014; Zhang et al., 2016). The Intergovernmental Panel on Climate Change also reported that global warming will increase the extremes of temperature (Meehl and Tebaldi, 2004; Solomon, 2007). Therefore, anticipating the effects of increasing occurrence of heat waves and cold spells on human health is crucial to establishing better public health strategies (Meehl and Tebaldi, 2004).

In order to assess the health burden due to climate change, temporal changes in the relationship between the extreme temperatures and mortality have become key issues in recent days (Chung et al., 2017; Gasparrini et al., 2015a). Relevant studies have reported temporal decline in the association between extreme heat and mortality, due to adaptation (Barnett, 2007; Bobb et al., 2014; Coates et al., 2014; Davis et al., 2003; Guo et al., 2012; Ha and Kim, 2013; Petkova et al., 2014). In addition, a recent multi-country study showed that the heat-mortality association decreased over the last decades, and the decline was more pronounced in the United States and Japan (Gasparrini et al., 2015a). Another study also reported that a decline in the heat-mortality association in summer (June to September) over time in three Northeast Asian countries (Korea, Japan, and Taiwan), and this decreasing trend was more pronounced in respiratory mortality, compared to all-cause mortality (Lee et al., 2018).

In addition, as record-breaking cold spells have occurred in recent years in the United States (Screen and Simmonds, 2014) and East Asian countries (AP, 2016; British Broadcasting Corporation, 2016), the importance of research on the impacts of cold spells on climate change has been on the rise. However, relatively fewer studies (Huynen and Martens, 2015; Kalkstein and Greene, 1997) focused on changes in the association between cold extremes and mortality over time (Åström et al., 2013; Chung et al., 2017; Vicedo-Cabrera et al., 2018), than heat-mortality association. A previous study reported that the population in Northeast Asia mal-adapted to cold temperature during the 1990s and

Abbreviations: ARF, attributable risk fraction; DLNM, distributed lag non-linear model; RR, relative risk

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2000s (Chung et al., 2017). In addition, another study showed that the temporal trends in attributable risk for cold temperature (higher than the location-specific minimum mortality temperature) varied by country (Vicedo-Cabrera et al., 2018). However, to the best of our knowledge, there is no research investigating the temporal changes in cold spell-related mortality during recent years in Asian countries.

Moreover, many previous studies have been limited in assessing the health burden of climate change, because most of them only denoted a temporal change in risk ratio of exposure (e.g., relative risk [RR]) (Bobb et al., 2014; Davis et al., 2003; Gasparrini et al., 2015a). Since the risk ratio does not consider the change in the distribution of extreme weather events, it could result in under- or over-estimation of mortality burden due to extreme events. A recent study showed that although the risk of mortality from heat decreased during recent decades in Japan, the mortality risk attributed to heat increased in the 2000s (2003 − 2012), compared to the 1970s (1972–1981), due to increased frequency of hot days in summer (Lee et al., 2018). The study also showed that erroneous conclusion regarding anticipating the future health impacts of heat temperature can be derived when only the risk of heat was considered, and suggested that the index for future health impacts considering the frequency and risk of heat should be used accordingly. Another study also reported that the time-trend of mortality burdens attributed to temperature, considering yearly-varying temperature distribution and the risks associated with temperature together, could be different from those estimated considering only considering risk changes (Vicedo-Cabrera et al., 2018).

Therefore, this study aimed 1) to estimate the temporal changes in the risks (RRs) of heat waves and cold spells on mortality in Korea and Japan, 2) to evaluate the temporal changes in the mortality burdens of heat waves and cold spells considering changes in their frequency during the study period, 3) to examine whether the changes in 1) and 2) are different in three regions (Korea, Japan-north, and Japan-south) separated by country and regional climates.

2. Methods

2.1. Data

This study includes time-series data for weather variables and all-cause mortality (as a daily mortality count) for 53 communities in two Northeast Asian countries: Korea (6 cities during 1992–2015), and Japan (47 prefectures during 1992–2015). Fig. S1 shows the geographical locations of 53 communities (divided into Korea, Japan-north, and Japan-south, which include 6, 24, and 23 communities; Japan-north and Japan-south was divided with the annual mean temperature within the range of 9.22–16.1 °C (corresponding to 0-50th percentiles of Japanese annual mean temperature) and of 16.1–23.2 °C (corresponding to 50-100th percentiles of Japanese annual mean temperature), respectively. Weather variables included daily mean temperatures (°C), and daily mean relative humidity (%). For each community, weather variables were measured from a single monitor station. The weather variables were originally hourly measured and 24-h average value were obtained for each community. Mortality data were obtained from the Korea National Statistics Office (Korea) and the Ministry of Health & Welfare of Japan (Japan), and weather data were obtained from the Korea Meteorological Office (Korea) and the Japan Meteorological Agency (Japan).

2.2. Definitions of heat wave and cold spell

In this study, daily mean temperature was used as an indicator of exposure to identify the effects of heat waves and cold spells on mortality. We defined heat waves as daily mean temperature above 95th (heat wave $_{>95\%}$), 97th (heat wave $_{>97\%}$), and 99th (heat wave $_{>99\%}$) percentiles of the temperature distribution with two or more consecutive days for each community during its study period. Also, we defined cold spells as daily mean temperature below 5th (cold spell $_{<5\%}$), 3rd (cold spell $_{<3\%}$), and 1st (cold spell $_{<1\%}$) percentiles of the temperature distribution with two or more consecutive days for each community during its study period. Although defining both heat waves and cold spells have not been standardized yet, numerous studies have used relative thresholds based on each community's mean temperature to define heat wave and cold spell (Anderson and Bell, 2011; Åström et al., 2013; Guo et al., 2017; Tong et al., 2015; Tong et al., 2014; Wang et al., 2016). This enables to reflect regional acclimatization considering each community's normal temperature (Guo et al., 2017), and facilitates comparing result of each community. We only used duration of two or more consecutive days to define heat wave and cold spell, because previous studies reported that definitions of heat wave and cold spell with two or more consecutive days provided more accurate statistical estimates (Tong et al., 2014) and the duration effect of extreme temperature was less relevant to increased mortality (Guo et al., 2017). And all days with temperature above (or below) the threshold vales for a given heat wave (or cold spell) definitions with two duration days were defined as heat wave (or cold spell) days (Guo et al., 2017).

2.3. Statistical analysis

The heat wave analyses were limited to the June to September (four hottest adjacent months), and the analyses for cold spell were limited to the December to March (four coldest adjacent months). The analyses for heat wave and cold spell were performed by individual model. The heat wave- and cold spell-mortality associations were analyzed using a two-stage time-series approach. In the first stage analysis, we applied a time-varying distributed lag model to estimate community-specific heat wave- and cold spell-mortality relationships with a linear interaction between year and exposures. The second-stage pooled these community-specific associations by meta-analysis. Those analytical approaches were referenced by previous studies (Gasparrini et al., 2015a; Gasparrini et al., 2015b; Guo et al., 2016).

2.3.1. First stage analysis

The first-stage used a generalized linear model with quasi-Poisson distribution. Firstly, we fitted the model to estimate heat wave- and cold spell-mortality associations respectively, with a year-interaction term for each community with the following specifications. The primary exposures, represented by binary indicators for heat waves and cold spells, were included using a distributed lag model structure. We used a basis function; a natural cubic spline including an intercept with two interval knots at equally spaced log values of lag days (up to 10 days for heat waves, and 21 days for cold spells) to capture flexible lag effects of heat waves and cold spells on mortality. We used a linear interaction term between year and basis to estimate the time-varying association between two exposures and mortality. And, to reflect consecutive days of December to March, we newly defined a “year” variable as the periods from December of previous year to March of the following year in cold spell analyses. For example, the period from December 2010 to March 2011 was re-defined as the 2011.

We also controlled the daily mean relative humidity (%) with cross-basis of distributed lag nonlinear model structure; a natural cubic B-spline with two internal knots (33.3rd, and 66.7th percentiles of location-specific relative humidity) for humidity dimension and a natural cubic B-spline with an intercept and two equally spaced knots on the log scale for lag dimension (up to 7 days). Seasonality was adjusted using a natural cubic B-spline with 4 degrees of freedom (df) for day of the hot (for heat wave) and cold (for cold spell) season within a year, respectively. Long-term trend was also controlled using a natural cubic B-spline of time on day with equally spaced knots and approximately 1 df every 10 years. The choices of lag days and modeling assumptions were referenced by previous extreme temperature-mortality studies (Gasparrini et al., 2015b; Guo et al., 2017).

From the first-stage analysis, we obtained four coefficients of the basis to represent the exposure-response relationships over the lags for each community by three decades. We defined three decades according to years of study period: the 1990s (1992–1999), the 2000s (2000–2009), and the 2010s (2010–2015), and obtained four coefficients for exposure-response associations over the lags for the centering years (1995.5, 2004.5, and 2012.5; the median years of each decade) of each of the three decades for each community. We reduced coefficients for each decade to a single coefficient respectively, which represents the overall lag-cumulative exposure-response associations (log values of relative risks of heat wave and cold spell). Also, we obtained four coefficients for an interaction between year and the basis, reduced those to a single overall cumulative community-specific interaction coefficient. The community-specific associations were used in the second-stage analysis. The first-stage analyses were performed using R statistical software and the *dlnm* package.

2.3.2. Second stage analysis

The community-specific associations (the lag-distributed association represented by four coefficients, and the overall cumulative association by a single coefficient) were pooled for each decade separately, using multivariate and univariate random effect meta-analysis. We pooled the estimates by each decade, separately for Korea, Japan-north, and Japan-south using meta-regression with an indicator for regions. And the univariate random effect meta-analyses also were used to derive the best linear unbiased prediction (BLUP) of the overall cumulative exposure-response for each community. Additionally, the multivariate random effect meta-analyses (Gasparrini et al., 2012) were used to pool the lag-distributed association in total population and for each sub-region, respectively. The second-stage meta-analyses were performed using R software and the *mvmeta* package.

2.3.3. Mortality attributable risk fraction of heat wave and cold spell

From the second-stage analysis, we derived the decade-specific overall lag-cumulative RR at heat wave (or cold spell) days, compared to non-heat wave (or non-cold spell) days, to estimate the attributable deaths and fraction in the next 10 days (or 21 days for cold spells), using a previously described method (Gasparrini and Leone, 2014). We used the overall lag-cumulative RRs corresponding to each heat wave (or cold spell) day by each decade to compute the daily attributed number of deaths by decades, as the product of the day's deaths and the daily attributable risk (=(RR-1)/RR) of the day.

The attributable number of deaths caused by heat waves (or cold spells) across by decades (the 1990s, 2000s, and 2010s) are given by the sum of the contributions from all the days of each decade, and its ratio with the total number of deaths during each decade provides the decade-specific the attributable fractions (ARFs, %). Furthermore, we inferred empirical 95% confidence interval using Monte Carlo simulations, with normal distribution assumption of the BLUP. These procedures for calculating the ARFs and their confidence intervals were described in previous researches (Gasparrini et al., 2015b). We described the detailed computation procedures in Supplementary Materials (Appendix 1. Details on the calculation of attributable risk fraction).

2.3.4. Testing the significance of temporal risk changes

The community-specific year-interaction coefficients for heat wave- and cold spell-mortality associations were pooled separately using univariate random-effect meta-analysis. We tested whether the interaction between year and heat wave (or cold spell) is significant (H_0: the lag-cumulative year-heat wave (or cold spell) interaction coefficient is zero). We used the pooled interaction coefficient, and applied univariate Wald test to examine if the pooled coefficient is not equal to zero. Additionally, in order to test whether there is a difference between the ARFs of the 2010s and the ARFs of the other decades (1990s and 2000s, respectively), we also applied Wald test between the corresponding ARFs (H_0: a difference between two ARFs is zero), based on independence hypothesis: the ARFs of two different decades were independently distributed. Mean and standard error of the ARFs for each decade were derived from the Monte Carlo simulations, described in above (a part for calculating an empirical confidence interval of the ARF).

2.3.5. Added effect of heat wave and cold spell

We also examined whether heat waves and cold spells had added effect on mortality after considering the effect of single day temperature. All other variables from first-stage model were maintained, only the temperature was controlled by using a cross-basis function in distributed lag non-linear model (Gasparrini et al., 2010). We modeled the temperature-response relationship using a natural cubic B-spline with three internal knots (placed at the 25th, 50th, and 75th percentiles of location-specific temperature distributions), lag-response (heat wave models: up to 10 days, cold spell models: up to 21 days) curve with natural cubic B-spline with two (cold spell models: three) internal knots placed at equally spaced values on the log scale. Procedures for second-stage analysis were maintained to pool the estimates of added effects of heat waves and cold spells.

2.3.6. Sensitivity analysis

In order to test the sensitivity of our results to the modeling parameters and assumptions described above, we calculated ARFs by decades with changing lag days (7 and 14 days for heat waves, and 14 and 28 days for cold spells), df for seasonality (df = 3 and 5), df for long term trend (df = 2), and duration days (three or more consecutive days). Additionally, we tried to report that how our main results change when the relative humidity, which is the prominent confounder on the heat wave (or cold spell)-related mortality, was not adjusted.

3. Results

The average and total number of heat waves and cold spells by decades (the 1990s, 2000s, and 2010s) are displayed in Table 1. In the total population, the yearly-average number of heat wave$_{>95\%}$ days decreased in the 1990s to 2000s, and increased in the 2010s (634.2 in the 1990s, 615.4 in the 2000s, and 1002 in the 2010s). The yearly-mean number of cold spell$_{<5\%}$ days in the total population increased during the 1990s to 2010s (468.5 in the 1990s, and 709.5 in the 2010s). The averaged numbers of heat wave and cold spell days in each year (from 1992 to 2015) are displayed in Fig. S2. Similar trends are shown in all other definitions for heat wave and cold spell, and for all sub-regions. Community-specific descriptive statistics, including death counts and temperature distribution during June to September (Table S1) and December to March (Table S2) are also shown in the Supplementary Materials. The community-specific counts for heat waves and cold spells during the whole study periods are reported in Fig. S3.

Fig. 1 (A) shows the RRs of heat waves (temperature unadjusted) by decades in the total population and according to regions with the results for the statistical test. The RRs of all heat waves significantly decreased during the study period in the total population (all *P*-values < 0.001). The significant-decreasing RR patterns were similar in Japan-north. However, in Japan-south and Korea, the RRs for heat waves did not significantly decrease over time (*P*-value > 0.05), except for heat wave$_{>95\%}$ in Japan-south. The corresponding community-specific RRs of heat waves by decades are reported in Fig. S4. And the pooled lag-response curves of heat waves by decades in the total population are represented in Fig. S6, it showed the highest RR at lag 0 days, and the RR decreased over lags with indications of delay up to 2–3 days, for all heat wave definitions. In addition, we could not find significant added effects of heat waves (Fig. 1 (B); temperature adjusted), except for heat wave$_{<99\%}$ for each decade.

On the other hand, as shown in Fig. 2 (A), the RRs for all cold spells (temperature unadjusted) significantly increased (all *P*-values: < 0.05) in the total population during the study period. In particular, the RR of

Table 1
Yearly averaged and total number of heat wave and cold spell defined by each three types of intense days in 53 communities of Korea and Japan.

Region (# of community)	Period	Yearly averaged number of days (Total number of days)					
		Heat wave $_{>95\%}$	Heat wave $_{>97\%}$	Heat wave $_{>99\%}$	Cold spell $_{<5\%}$	Cold spell $_{<3\%}$	Cold spell $_{<1\%}$
Total population	Whole	718.3	386.1	100.4	558.8	292	72.4
(53)		(17,240)	(9267)	(2409)	(13,411)	(7008)	(1738)
	1990s	634.2	346.6	101	468.5	248.4	58.8
	(92–99 y)	(5074)	(2773)	(808)	(3748)	(1987)	(470)
	2000s	615.4	290.6	60.1	540.6	277.1	71.6
	(00–09 y)	(6154)	(2906)	(601)	(5406)	(2771)	(716)
	2010s	1002	598	166.7	709.5	375	92
	(10–15 y)	(6012)	(3588)	(1000)	(4257)	(2250)	(552)
Japan-north	Whole	323.1	174.2	43.7	253.3	133.6	34.2
(24)		(7754)	(4182)	(1048)	(6080)	(3206)	(820)
	1990s	281.8	155.1	44.8	202.5	112.6	31.2
	(92–99 y)	(2254)	(1241)	(358)	(1620)	(901)	(250)
	2000s	247.9	114	25.8	253.3	127.6	32.9
	(00–09 y)	(2479)	(1140)	(258)	(2533)	(1276)	(329)
	2010s	503.5	300.2	72	321.2	171.5	40.2
	(10–15 y)	(3021)	(1801)	(432)	(1927)	(1029)	(241)
Japan-south	Whole	314.5	167.6	44.2	240.2	123.3	29.5
(23)		(7549)	(4022)	(1062)	(5766)	(2959)	(709)
	1990s	264.8	139.6	38.6	210.4	111.6	24.8
	(92–99 y)	(2118)	(1117)	(309)	(1683)	(893)	(198)
	2000s	302.7	144.8	29.5	230.7	118	30.3
	(00–09 y)	(3027)	(1448)	(295)	(2307)	(1180)	(303)
	2010s	400.7	242.8	76.3	296	147.7	34.7
	(10–15 y)	(2404)	(1457)	(458)	(1776)	(886)	(208)
Korea	Whole	80.7	44.3	12.5	65.2	35.1	8.7
(6)		(1937)	(1063)	(299)	(1565)	(843)	(209)
	1990s	87.8	51.9	17.6	55.6	24.1	2.8
	(92–99 y)	(702)	(415)	(141)	(445)	(193)	(22)
	2000s	64.8	31.8	4.8	56.6	31.5	8.4
	(00–09 y)	(648)	(318)	(48)	(566)	(315)	(84)
	2010s	97.8	55	18.3	92.3	55.8	17.2
	(10–15 y)	(587)	(330)	(110)	(554)	(335)	(103)

the highest intensity cold spell (cold spell $_{<1\%}$) increased more rapidly over time in Japan-south (RR: from 1.05 in the 1990s to 1.16 in the 2010s) and Korea (RR: from 0.71 in the 1990s to 1.54 in the 2010s), than in Japan-north (RR: from 1.02 in the 1990s to 1.12 in the 2010s). Cold spell $_{<3\%}$ showed a similar time-pattern of RR as cold spell $_{<1\%}$. The corresponding community-specific RRs of cold spells by decades are reported in Fig. S4, while the pooled lag-response curves of cold spells by decades in the total population are represented in Fig. S6. It showed the highest RR at lag 1–3 days, and the RR decreased over lags with indications of delay up to 15–20 days for all intensities of cold spells. In addition, we could not find significant added effects of cold spells (Fig. 2 (B); temperature adjusted) for each decade.

Temporal changes in ARFs due to heat waves and cold spells are shown, and the statistical test results for the ARF changes in the 2010s compared to other periods (H_0: the heat wave ARFs of the 1990s or 2000s are equal to that of the 2010s) are presented in Fig. 3. In the total population, the ARF of heat wave $_{>95\%}$ declined significantly in the 2010s (0.31%) compared to 1990s (0.64%) with *P*-value < 0.001. The ARF in the 2010s also decreased compared to the 2000s (0.39%), although this difference was not statistically significant (*P*-value = 0.152). On the other hand, the ARFs of heat wave $_{>97\%}$ and heat wave $_{>99\%}$ in 2010s (0.34% and 0.22%, respectively) has increased compared with those of the 2000s (0.27% with *P*-value = 0.078, and 0.12% with *P*-value = 0.001, respectively). These increased patterns for heat wave $_{>97\%}$ and heat wave $_{>99\%}$ ARFs was more prominent in Japan-south. These trends were considered to be related to the increasing frequency of heat waves in the 2010s, compared to the 2000s (Table 1). The corresponding attributable number of deaths due to heat waves is displayed in Table S3.

Changes in mortality ARF to cold spell over time and the corresponding statistical test results (H_0: the cold spell ARFs of the 1990s or 2000s are equal to those of the 2010s) are also reported in Fig. 3. In the total population, the ARFs of all definitions for cold spell significantly increased in the 2010s (1.44% for cold spell $_{<5\%}$, 1.13% for cold spell $_{<3\%}$, and 0.38% for cold spell $_{<1\%}$, with all the corresponding *P*-values < 0.001) compared to both the ARFs of the 2000s and 1990s. These decreasing trends over time have been observed to be consistent in all sub-regions. These ARF time trends were presumed to reflect both the increase in cold spell RR (Fig. 2) and the increase in frequency of cold spells during the study period (Table 1). The corresponding attributable number of deaths due to cold spells is displayed in Table S3, and the community-specific ARF of heat wave and cold spell by decades are reported in Fig. S5.

Fig. 4 shows interaction coefficients (BLUPs for interaction coefficient from second-stage analysis) between year and heat wave $_{>99\%}$ (top left) and cold spell $_{<1\%}$ (bottom left). Although some communities had positive interaction coefficients, most communities showed a decreasing trend of the heat wave-mortality association (log value of RR) over time. This declining pattern was more pronounced in the Japan-south. On the other hand, increasing trends of log valued RR for cold spells were found across all regions in both countries; this increasing trend was more pronounced in Korea and Japan-south. In addition, Fig. 4 also contains the differences in ARF of heat waves (top right) and cold spells (bottom right) in the 2010s compared to the 2000s. In considerable number of communities in Korea and Japan-south, the ARFs of heat wave showed increasing trends in the 2010s, although the communities showed temporal decreases in the corresponding RRs. On the other hand, the ARFs of cold spell increased in the 2010s in most communities compared to the 2000s. Figs. S7–S8 represent the corresponding figures with different heat wave and cold spell definitions, and similar trends were observed as Fig. 4.

In the sensitivity analysis, our main conclusions were robust to the

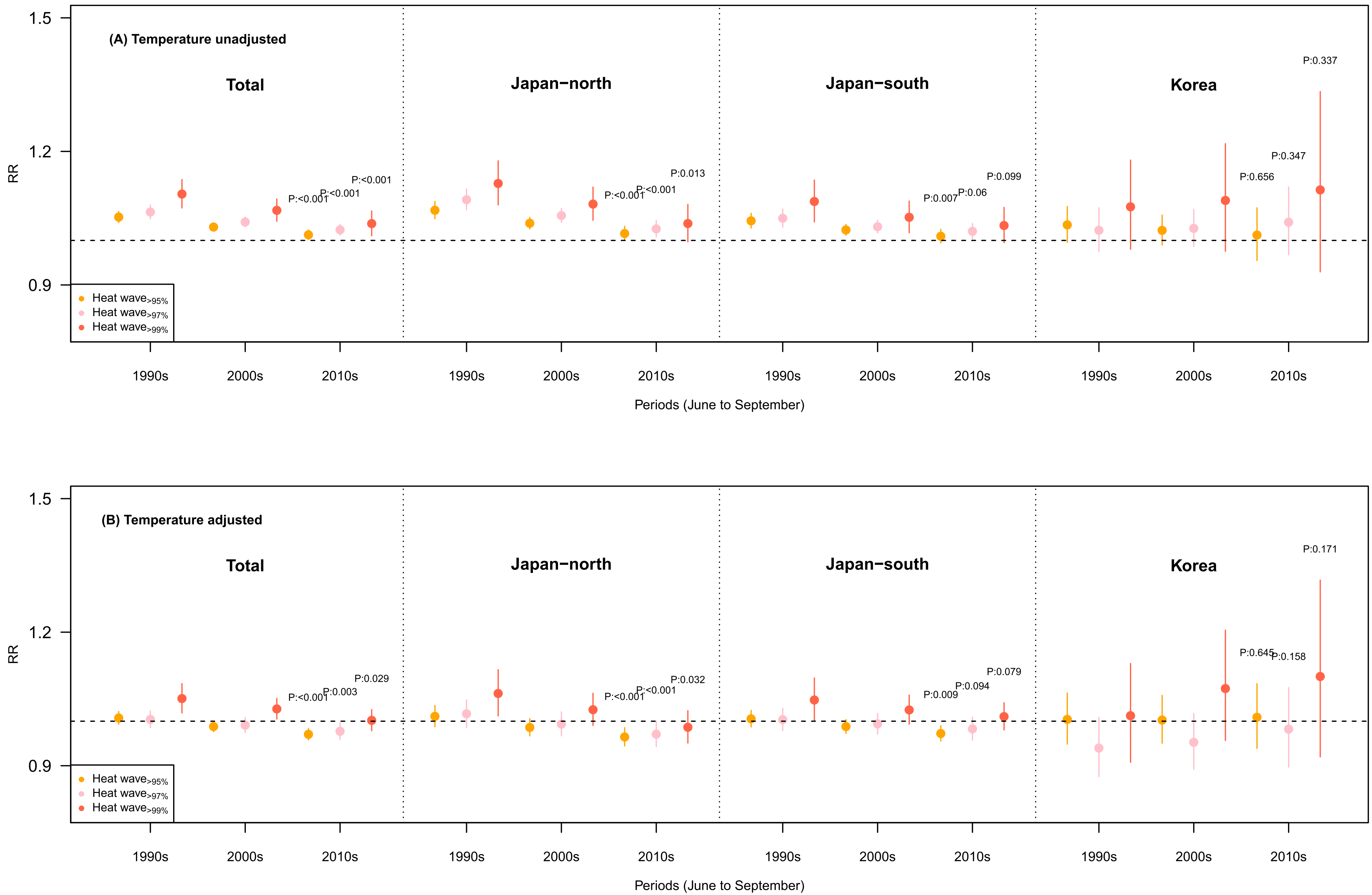

Fig. 1. Temporal changes in cumulative relative risks (RR) of heat waves on mortality by decades (the 1990s: 1992–1999, 2000s: 2000–2009, and 2010s: 2010–2015) in the total population and by the three regions, with results from Wald type tests (H_0: the year-heat wave (or cold spell) interaction coefficient is zero; *P*: *P*-value). (A): overall effects of heat waves, (B) added effects of heat waves after controlling for the effects of daily mean temperature.

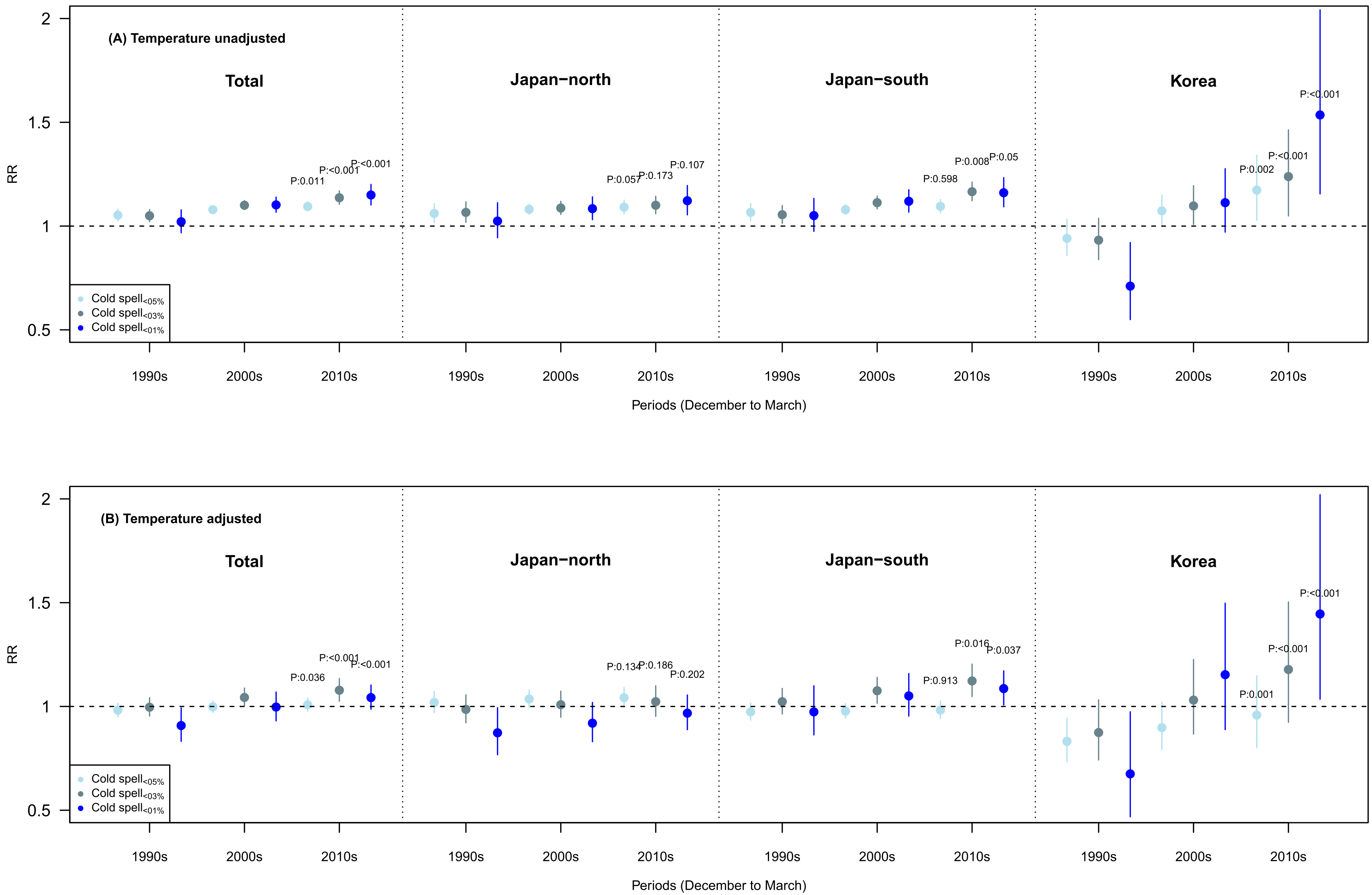

Fig. 2. Temporal changes in cumulative relative risks (RRs) of cold spells on mortality by decades (the 1990s: 1992–1999, 2000s: 2000–2009, and 2010s: 2010–2015) in the total population and by the three regions, with results from Wald type tests (H_0: the year-heat wave (or cold spell) interaction coefficient is zero; *P*: *P*-value). (A): overall effects of cold spells, (B) added effects of cold spells after controlling for the effects of daily mean temperature.

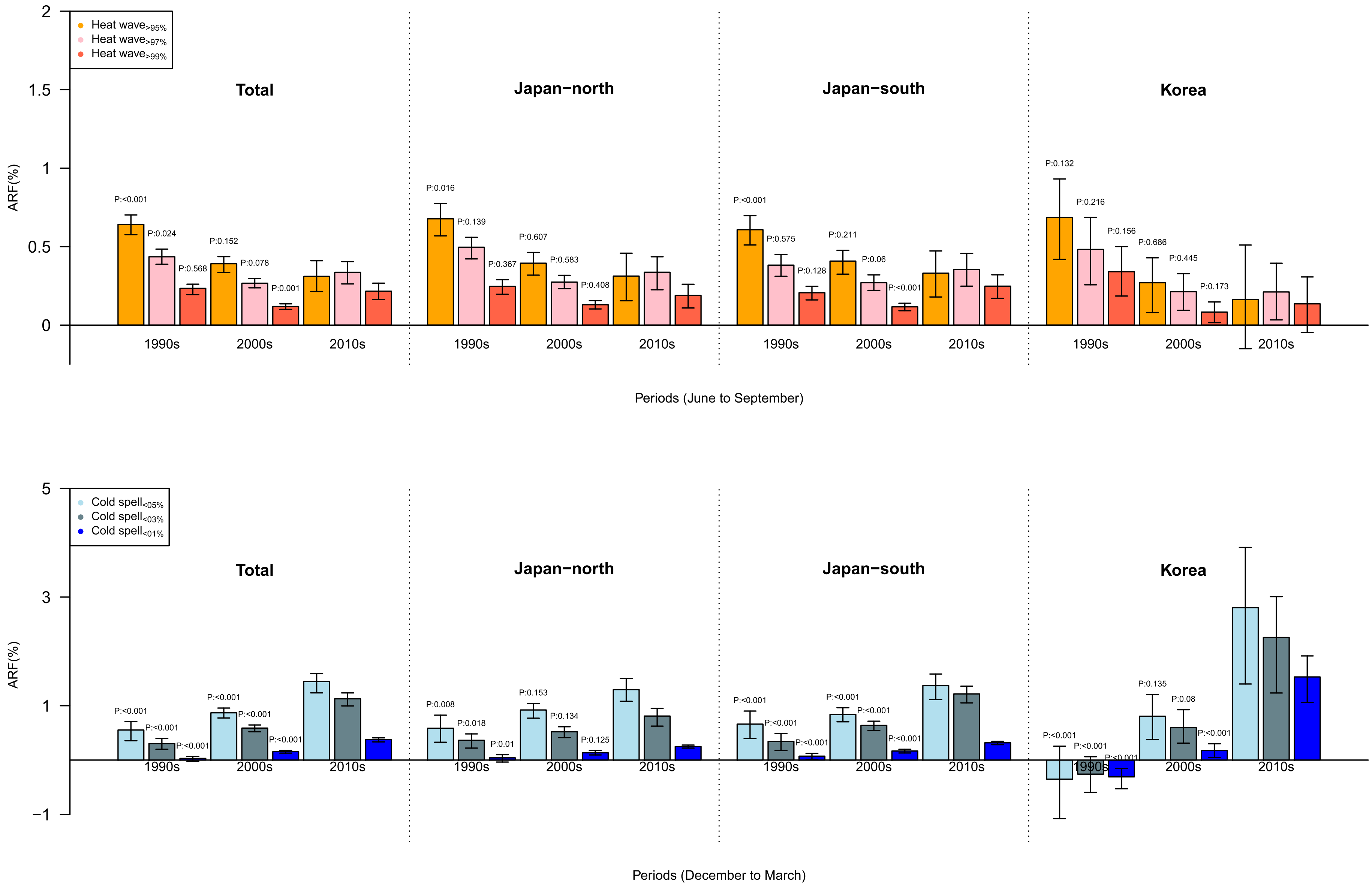

Fig. 3. Temporal changes in mortality attributable risk fraction (ARF) of heat wave (top) and cold spell (bottom) by decades (the 1990s: 1992–1999, 2000s: 2000–2009, and 2010s: 2010–2015) in the total population and by the three regions with results from Wald type tests (H_0: the ARF in the 1990s (or in the 2000s) is the same as the ARF in the 2010s; P: P-value).

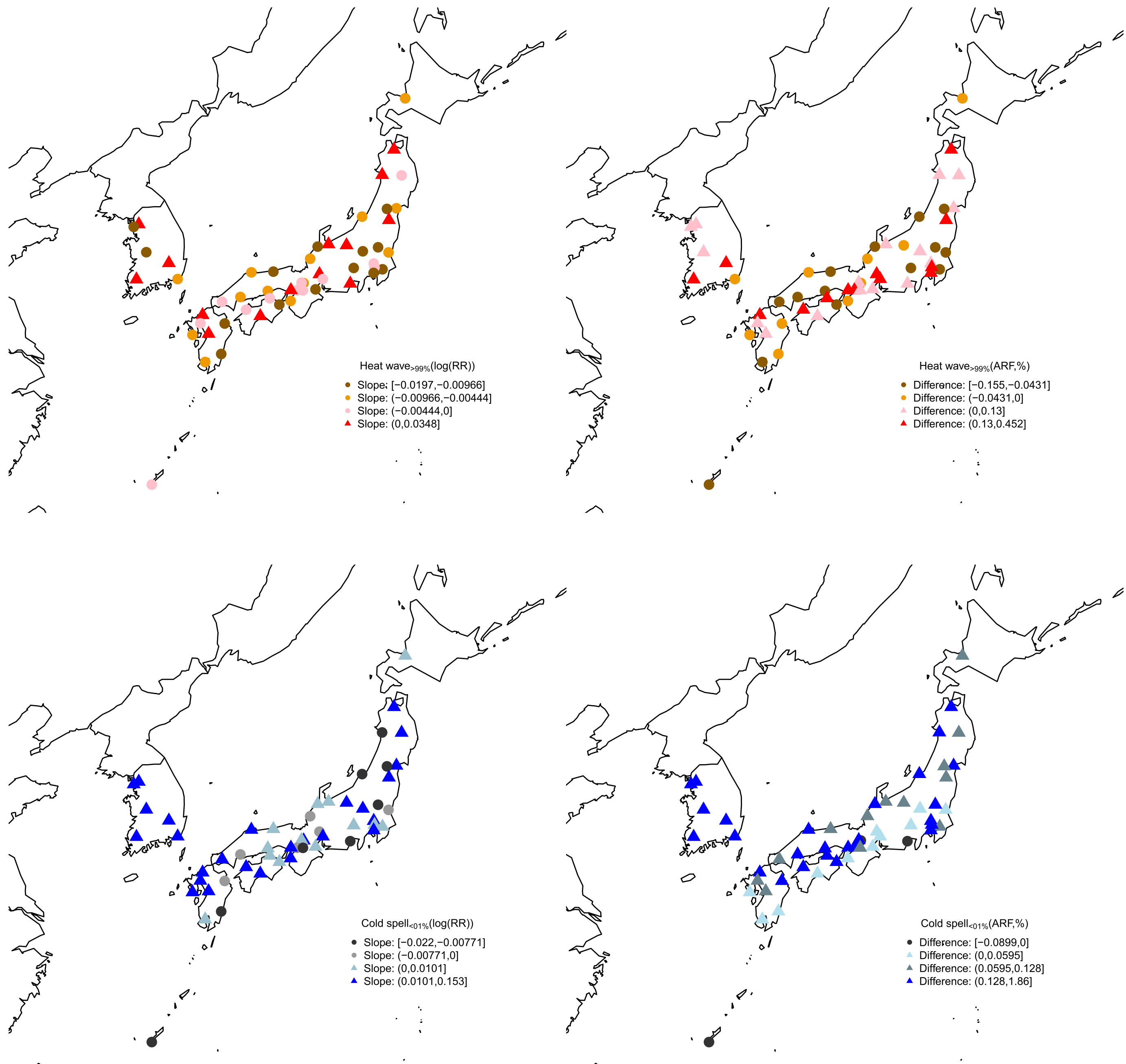

Fig. 4. Geographical distribution of year-interaction coefficients for the heat wave $_{>99\%}$- and cold spell $_{<1\%}$-mortality association, and differences of mortality attributable risk fractions (ARF) of heat wave $_{>99\%}$ and cold spell $_{<1\%}$ between the 2010s (2010–2015) and 2000s (2000–2009).

choice of model conditions (Table S4). When the modeling specifications were changed, the results were generally consistent, suggesting that the ARFs of heat waves increased in the 2010s compared to the 1990s, except for heat wave $_{<95\%}$. The ARFs for all cold spells increased during the study period. In addition, we found that the risk of both exposures decreased after relative humidity adjustment, although the decrease was too small to affect the significance of the overall exposure-response relationship (Table S5).

4. Discussion

In this study, we observed that the average number of heat waves and cold spells increased in the 2010s compared to the 2000s in Korea and Japan. This study also provides evidence of temporal decreases in the RRs of heat waves for all intensities of heat wave in the total population. On the other hand, most RRs for cold spells significantly increased during the study period in the total population, and more pronounced increases were observed in Japan-south and Korea. Taking into account the time-varying RRs and frequencies of extreme events, the ARFs of both heat waves and cold spells increased in the 2010s, compared to those in the 2000s, except for low intense heat wave (heat wave $_{<95\%}$). These results were related to increased frequencies of heat waves and cold spells in the 2010s compared to the 2000s.

The results of our study show a temporal decrease in RR patterns of heat waves, which can be interpreted as an adaptation. This finding has been described in previous studies. A previous study showed that the risk of heat temperature has declined during recent decades in multiple countries (Gasparrini et al., 2015a). Other studies reported that the excess mortality during the 2006 heat wave was markedly lower than the predicted mortality estimated from the model using summer

temperature data from 1975 to 2003 in France (Fouillet et al., 2008), and also described that heat-related mortality rates declined over time, with 41.0 averaged-excess heat-related deaths per year in the 1960s and 10.5 in the 1990s for 28 metropolitan areas in the U.S. (Davis et al., 2003). Increasing air conditioning prevalence, physiological acclimatization, demographic or socioeconomic factors, and improvements in housing have been suspected as the drivers of these decreasing patterns (Fouillet et al., 2008; Gasparrini et al., 2015a; Kyselý and Kříž, 2008). In addition, prevention plans, such as heat-surveillance systems and other public health interventions, have presented as one of the possible reasons of the reduced heat effects on mortality (Kovats and Kristie, 2006). However, this topic should be more discussed in further, and the corresponding prevention plans should be developed continuously to minimize the effect of extreme heat temperatures.

On the other hand, relatively few studies have described the temporal changes in the cold-mortality association, and the results were still mixed. Åström et al. (2013) showed that the number of cold extremes increased in 1980–2009 (251) compared to 1900–1929 (220); however, the RR of cold extremes did not statistically relate with the increase in frequency (Åström et al., 2013). Also, Chung et al. reported that cold-related mortality remained constant over decades (from 1972) and slightly increased in the late 2000s. In another previous study, Vicedo-Cabrera et al. (2018) showed that the temporal pattern of ARF for cold were heterogeneous among 10 countries, unlike the pattern of ARF for heat which declined over time in most countries (Vicedo-Cabrera et al., 2018). In that study, the ARF due to cold in the 2000s decreased compared to the 1990s in Japan, which can be interpreted differently with our results. However, the differences should be interpreted with caution. Although there are some differences in the study period and analytic conditions used in each study, we believe the most important difference lies in the definition of "cold." Whereas the "cold" can be interpreted as cold spell days in our study, Vicedo-Cabrera et al. defined the "cold" day as all temperatures higher than the minimum mortality temperature and calculated the ARF during all the cold days. However, their study also reported that the risk of extreme cold (1st percentile vs. percentile of minimum mortality temperature) increased over time in Japan (RR: 1.364 in 1985, 1.371 in 2012), therefore the results of both studies might be similar if similar definition for "cold" was used.

Furthermore, the reason why the risks of cold spell have increased over time should be more discussed. A recent study in 15 metropolitan cities in three Northeast Asian countries suggested "acclimatization" as a hypothesis of mal-adaptation to cold (Chung et al., 2017). The study represented prior studies which showed that people in warmer weather were generally more sensitive to cold temperature (Anderson and Bell, 2009; Guo et al., 2014), and suggested that the trend of warmth could make people more vulnerable to cold temperatures. In our study, the RRs of cold spells increased during the study period, and the increasing trend was more prominent in Japan-south which has a relatively hotter climate than Japan-north. Therefore, although limited evidence, our findings may support the acclimatization hypothesis related to cold spells. And also, our results implicate the need for more interventions for cold spell in both Asian countries. Despite technological advancements (such as early warning system), the increasing cold spell effect suggests that researchers will need to focus on the causes and countermeasures for temporal increase in cold spell effects.

The temporal trend of heat wave/cold spell-mortality association was generally consistent both with time-constant percentiles and with time-dependent percentiles used to define the threshold temperature points of heat wave and cold spell (Fig. S9). The thresholds of heat wave and cold spell were similar between the 1990s and 2000s; however they were substantially different in the 2010s, as a result of warmer temperature distribution (Table S6). We selected the time-constant threshold percentiles as the main approach, because the time-constant percentiles took into account the average threshold points across the entire study period. However, further discussions are needed as to whether the definition of time-constant percentiles should be applied in the studies for anticipating future impacts of heat waves and cold spells, because the time-constant percentiles approach might have a limitation in reflecting acclimatization to a warming climate, as the study period would be longer. In addition, the fact that the temporal risk trends were maintained even after considering the varying threshold points by period may indicate that there might be non-climatic factors (such as lifestyle and technological advancements) that could affect adaptation to extreme temperatures (Vicedo-Cabrera et al., 2018). These factors should be importantly considered to find suitable definitions for heat wave and cold spell in the future, and we believe that further studies are needed to find the optimal heat wave and cold spell definitions taking into account the various factors.

The interesting finding of our study was that the temporal change pattern of ARF differed with the changes in RR. In particular, the RRs of heat waves$_{< 97\%}$ and heat wave$_{< 99\%}$ in the 2010s decreased, compared to those in the 2000s (Fig. 1 (A)); however, those ARFs in the 2010s increased, compared to the 2000s (Fig. 3). This result indicates that the health burden of heat wave may increase with future climate change, even with the population partly adapted to heat wave. Most previous studies evaluating the temporal changes in the health impact of extreme events only focused on RR (Bobb et al., 2014; Carson et al., 2006; Gasparrini et al., 2015a). However, this could cause a misunderstanding of the future health burden of extreme temperature, unless the increasing frequency is considered. Since extreme weather events are expected to be increase with climate change (Meehl and Tebaldi, 2004; Solomon, 2007), our study suggests that ignoring the temporal changes would result in considerable over/underestimated impacts of heat wave/cold spell under climate change.

We performed analyses to detect the added effects of heat wave and cold spell by decomposing the effects of heat wave and cold spell into temperature and added effects, and found that heat wave and cold spell nearly did not have added effects on mortality (Fig. 1 (B), and Fig. 2 (B), except for highly intense heat wave (heat wave$_{> 99\%}$) and cold spell (cold spell$_{< 1\%}$). These results are consistent with previous studies conducted to estimate the added effect of extreme events (Barnett et al., 2012; Gasparrini and Armstrong, 2011). However, we reported the effects of heat wave and cold spell without separation with main temperature effect, for two major reasons. First, it was for concise interpretation of heat wave and cold spell impact. Warning systems also do not distinguish the concepts of main temperature and duration effects (Robinson, 2001). Second, it is controversial to describe the effect of heat wave and cold spell as a part of temperature effects, and the complexity of heat wave (or cold spell) effects is still insufficient to be accounted for by concepts of the main effect of heat (or cold) and added effect of sustained heat (or cold) (Xu et al., 2016). For those reasons, many previous studies selected the modeling approach to estimate the effect of heat wave and cold spell without decomposing the main and added effects (Åström et al., 2013; Guo et al., 2017; Tong et al., 2015; Tong et al., 2012; Xu et al., 2016).

Furthermore, our study can support the formulation of a definition of heat wave based on local climatic conditions (Fig. S4). Firstly, in most communities, we found that the heat wave RR of mortality was significant at the 95th percentile of community-specific temperature, increased at the 97th percentile and sharply rose at the 99th percentile during the entire study period. This trend is consistent with the results of previous studies (Guo et al., 2017; Tong et al., 2015; Tong et al., 2014), and implies that a more effective heat wave alert is needed as daily temperature increases. However, some communities in Kyushu (the island in the southernmost part of the four major islands in Japan: Fukuoka, Nagasaki, Kumamoto, etc. in Fig. S4) showed a decreasing trend of heat wave RR (or did not increase) at the 99th centile, compared to the RR at the 97th centile. We assumed that the reversed pattern might have arisen from regional acclimatization (Anderson and Bell, 2009; Guo et al., 2017), and that adaptation to extreme hot temperature may be more crucial in the hottest area than other areas (Guo

et al., 2017). Therefore, the cut-off for the definition of heat wave in the hottest region should be set lower than that of other regions. In addition, our results also imply that the definition for heat wave needs to be modified over time, because the heat wave RR at the 99th centile was lower than that at the 97th or 95th centiles in a considerable number of communities in the 2010s. This trend can be related to avoidance of the outdoors due to the weather forecast or use of air conditioner on extremely hot days during the recent period (Gasparrini et al., 2015a, 2015b). Thus, in order to establish a more efficient heat wave warning system, a lower cut-off of heat wave definition should be considered than in the past.

Unlike the heat wave, our results suggest that a slightly different approach seems necessary to define cold spell (Fig. S4). In Japan-north and Korea, many communities showed higher cold spell RRs at the 5th and 3rd centile than the RR at the 1st centile in the 1990s; however, the RR at the 1st centile was higher than that at other centiles in the 2010s. On the other hand, in a substantial number of communities in Japan-south, there was no distinct pattern between cold spell RR and cut-off points in the 1990s; however, they showed higher RRs for cold spell at the 3rd centile than that at the 1st percentile after 2010, similar to the results obtained in the 1990s for Japan-north. Although there may be several plausible explanations for these temporal patterns (such as changes in outdoor/indoor activities, income level, or public health interventions), we conjecture that the acclimatization to warming climate may be a possible hypothesis. As described above, people in warmer weather were generally more vulnerable to cold (Anderson and Bell, 2009; Guo et al., 2014); thus, the temporal warming climate could make people became more sensitive to the high-intensity of cold spell. However, since there was no consistent pattern among all communities and in many communities of Japan-south, the cold spell RR at the 1st centile was still less than the RR at the 3rd centile; thus, this hypothesis should be discussed comprehensively in further studies. Nevertheless, the results of the study support the need for regional- and period-specific cold spell definitions in order to develop effective warning systems across the communities. After 2010, a more high-level cold spell warning system was needed as daily temperature declined in Japan-north and Korea, and the alert for mild-cold spell (5th and 3rd centiles) may be more efficient than the alarm for extreme cold spell (1st centile) in Japan-south.

Finally, we acknowledge several limitations in our study. First, age-specific heat wave- and cold spell- mortality relationships could not be considered. Because differential adaptations to heat according to age were also reported in a previous study (Bobb et al., 2014), the age-specific analysis should be conducted in future studies. Second, our study did not consider air pollution which could be a confounder of temperature, because the data were not available. Third, the current findings cannot be interpreted as being representative of other communities and countries with different socioeconomic characteristics and climatic conditions, because this study was conducted in only two Northeast Asian countries (Korea and Japan). Therefore, future studies should strive to overcome these limitations by expanding the study populations and data collection.

5. Conclusion

We examined the temporal changes in the impact of heat wave and cold spell on mortality during 1992–2015 in 53 communities in Korea and Japan. As a result, the pooled RRs of heat waves decreased in the 2010s in the total population, while the RRs of cold spells increased in the 2010s, compared to other decades. These results support the evidence that the population in the two countries were adapted to heat waves; however the population had maladapted to cold spells during recent decades. In addition, we observed the increases in averaged frequency of heat waves and cold spells in the 2010s compared to the 2000s in the total population, and the ARFs of heat waves and cold spells also showed increasing trend during the same period as results of considering increases in their frequency. These findings suggest that the health burden of extreme events can increase with climate change even if the population adapts to extreme events gradually. Furthermore, we expect that our study can attribute to advanced public health policies and multinational efforts aimed at reducing extreme weather events.

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Competing financial interest

The authors declare they have no actual or potential competing financial interests.

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